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Recent advances in the development of the aluminum stabilized NbTi superconductor have great potential for military and commercial applications such as mine sweeping and magnetic resonance imaging (MRI). Producing long, low-cost conductors requires either improving the current technology or developing new approaches to aluminum cladding and conductor forming processes. However, these cladding and forming processes should be coupled with concurrent product and process design based on material properties and simulation models. The Program Executive Office, Mine Warfare, tasked the National Center for Excellence in Metalworking Technology (NCEMT) to asses the current state-of-the-art in cladding technology for NbTi superconductors, based on interactions with commercial companies and the Naval Surface Warfare Center (NSWC), Annapolis Detachment, and a thorough review of the technical literature. This report presents several potential commercial technologies and their advantages and disadvantages. Out of the five different approaches to aluminum cladding, extrusion and electroplating methods are the least applicable due to their batch-type operations with inherently limited conductor plating length capability. The three other methods of aluminum cladding include radial wrapping, linear wrapping, and molten metal coating. While each method has technical challenges, all three have capabilities to continuously clad aluminum for the required conductor lengths. Benefits derived from a successful aluminum cladding technology include a 40-50% weight reduction over equally sized all-copper-stabilized wire, improved thermal stability (10 times) of the magnet system, and a 25-30% decrease in manufacturing cost. Based on the evaluative efforts at the NCEMT and the NSWC, the most technically feasible and affordable method will be selected for further development. This technique will be optimized either at the NCEMT or at the facility of a commercial company interested in the manufacture of aluminum stabilized NbTi superconductors.

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Process and Cost Optimization of Aluminum Stabilized NbTi Superconducting Wire

Assessment of Cladding Technologies for Aluminum Stabilized NbTi Superconducting Wire

Phase I - Technical Feasibility

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July 24, 1997

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JK/bem

EXECUTIVE SUMMARY

Recent advances in the development of the aluminum stabilized NbTi superconductor have great potential for military and commercial applications such as mine sweeping and magnetic resonance imaging (MRI). Producing long, low-cost conductors requires either improving the current technology or developing new approaches to aluminum cladding and conductor forming processes. However, these cladding and forming processes should be coupled with concurrent product and process design based on material properties and simulation models.

The Program Executive Office, Mine Warfare, tasked the National Center for Excellence in Metalworking Technology (NCEMT) to assess the current state-of-the-art in cladding technology for NbTi superconductors, based on interactions with commercial companies and the Naval Surface Warfare Center (NSWC), Annapolis Detachment, and a thorough review of the technical literature. In September 1997, the NCEMT, in cooperation with the NSWC, conducted a workshop on aluminum stabilization of the NbTi superconductor. As a result, the NCEMT evaluated several technical approaches to produce aluminum-clad superconductors. This report presents several potential commercial technologies and their advantages and disadvantages.

Out of the five different approaches to aluminum cladding, extrusion and electroplating methods are the least applicable due to their batch-type operations with inherently limited conductor plating length capability. While the proof-of-concept demonstration for both these processes could be successful, full-scale production runs of 30,000 feet in length are not feasible. The three other methods of aluminum cladding include radial wrapping, linear wrapping, and molten metal coating. While each method has technical challenges, all three have capabilities to continuously clad aluminum for the required conductor lengths.

Benefits derived from a successful aluminum cladding technology include a 40-50% weight reduction over equally sized all-copper-stabilized wire, improved thermal stability (10 times) of the magnet system, and a 25-30% decrease in manufacturing cost.

The NCEMT efforts will have a two-fold impact on the Advanced Lightweight Influence Sweep System (ALISS) program. First, an aluminum-stabilized NbTi/Cu superconductor with a higher thermal stability will reduce the magnet weight to approximately 44% of that of an equally sized, all-copper-stabilized wire. This conductor will be incorporated in the spare

magnet for the ALISS Advanced Technology Demonstration (ATD) and could be made available for use in the joint service ATD in FY98. Second, an all-aluminum-core superconductor will reduce conductor weight by an additional 26%. This conductor would be immediately specified in FY99 during the follow-on ALISS acquisition program.

Based on the evaluative efforts at the NCEMT and the NSWC, the most technically feasible and affordable method will be selected for further development. This technique will be optimized either at the NCEMT or at the facility of a commercial company interested in the manufacture of aluminum stabilized NbTi superconductors.

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1.0 INTRODUCTION

This report describes the results of the National Center for Excellence in Metalworking Technologies (NCEMT's) efforts in evaluating potential technologies for producing aluminum stabilized NbTi superconductor. The objective of the Process and Cost Optimization of Aluminum-Stabilized NbTi Superconducting Wire project is to provide the Program Executive Office, Mine Warfare and the Naval Surface Warfare Center (NSWC), Annapolis Detachment, with an assessment of the current state-of-the-art in the aluminum cladding technology of NbTi superconductors. The aluminum stabilized NbTi superconductor is a critical component of the mine sweeping system (ALISS).

Currently, the only successful aluminum stabilization of NbTi/Cu superconductor was demonstrated using a hot co-extrusion process. The process is limited in its capability to clad very long conductors (30,000 feet) and is very costly. The analysis of a quote for the manufacture of aluminum stabilized wire (specific production unit of 60,000 feet and 1:1 copper/NbTi ratio) given to the U. S. Navy, in January 1995, estimates the cost of co-extrusion process as 60% of total cost ($1.24/foot) of the conductor. This analysis provides a strong incentive to develop an alternative cladding technology with continuous length capability and significant cost reduction.

The technology of material cladding covers the whole range of materials, including paper, glass, polymers, ceramics, and metals. During the project studies, the NCEMT contacted prospective companies for specific cladding technologies that could be applied to the aluminum cladding of superconductors. The NCEMT efforts concentrated on the technologies of radial wrapping, linear wrapping, molten metal dip coating, extrusion, and electroplating. However, while this assessment may provide a reasonable conclusion on the technical feasibility of a specific cladding process, the cost analysis can be applied only to the results of the experimental work which will be conducted in the follow-up project.

2.0 BACKGROUND

The Chief of Naval Operations is concerned about the loss of tactical advantage because no current system can provide in-stride mine clearance, especially in shallow water. The ongoing ALISS ATD has shown that superconducting technology provides the first significant advance in magnetic influence mine-sweeping capability since World War II.

The NSWC, Annapolis Detachment, has awarded General Atomics a contract to build a conductively cooled superconducting magnet system (magnet cooled by mechanical cryogenic refrigerators, not liquid cryogen) to meet the in-stride mine sweeping requirements. The weight of the ALISS is a critical design parameter. The magnet system should be as light as possible without sacrificing magnet stability during 100-g shock loads and severe vibration conditions. An aluminum-stabilized NbTi/Cu superconducting wire will meet these performance requirements for mine sweeping systems and exceed those of equally sized, all-copper-stabilized wires.

The aluminum stabilization of composite superconductors was pursued for the last 20 years due to the unique advantages of high purity aluminum over those of copper. These include negligible magnetoresistance, low density, radiation transparency, high residual resistivity ratio, and ease of forming. These aluminum-stabilized superconductors are particularly suitable for large magnet applications such as high field magnetic resonance imaging (MRI), high energy physics particle detectors, isotope separation magnets, magnets for fusion energy development and superconducting magnetic energy storage (SMES).

Aluminum stabilization is achieved by either co-extrusion [1-5] or soldering [6]. The NSWC investigated electrical and mechanical properties of aluminum-stabilized NbTi superconducting wires as part of the Superconducting Propulsion Project of the Surface Ship Technology Block Program [7-8]. While substantial improvements in conductor properties and cladding technology were made, the conductor cost is prohibitive for military and commercial applications. The effort of this study was to evaluate alternative cladding technologies which have potential for significantly reducing the cost of the finished product

evaluate alternative cladding technologies which have potential for significantly reducing the cost of the finished product

3.0 TECHNICAL ASSESSMENT - ALUMINUM CLADDING

3.1 GENERAL ASPECTS

Extrusion, linear wrapping and welding, radial (spiral) wrapping, molten metal coating, and electroplating methods are available for applying aluminum metal onto a superconducting wire. Three major factors which need to be considered before a functional conductor is manufactured are cost, thermal stability, and superconducting properties of the clad conductor. Under the operating conditions, the copper/aluminum interface bonding plays a crucial role in the thermal stability of the conductor. Inadequate bonding may disrupt the heat flow locally and affect the conductor's thermal stability. In other words, the superconductor may exceed the critical temperature T_c and cease to be superconducting. The cost is affected by the nature of the cladding process (batch vs. continuous) and the capital cost of the equipment.

This evaluation will determine the impact of each cladding process on the cost and on the thermal stability of the conductor. The following sections describe the advantages and disadvantages of each cladding process.

3.2 EXTRUSION

Currently, the only proven process for cladding aluminum onto a superconducting wire is the hot co-extrusion process developed by R & R Engineering. As shown in Figure 3-1, this process involves passing a finished size superconductive wire through a mandrel with the exit point at the entrance of a forming die. The heated aluminum billet is pressed around the mandrel and through the forming die. The resulting friction between the aluminum and the core wire is sufficient to draw the core wire through the die. The shear stress created at this interface causes the materials to bond metallurgically. Compared with a simple mechanical bond, a metallurgically bonded

interface is advantageous because it decreases the thermal barrier by providing more fresh metal contact surface. The round coated wire is then twisted and shaped into a rectangular cross-section using the Turks Head machine.

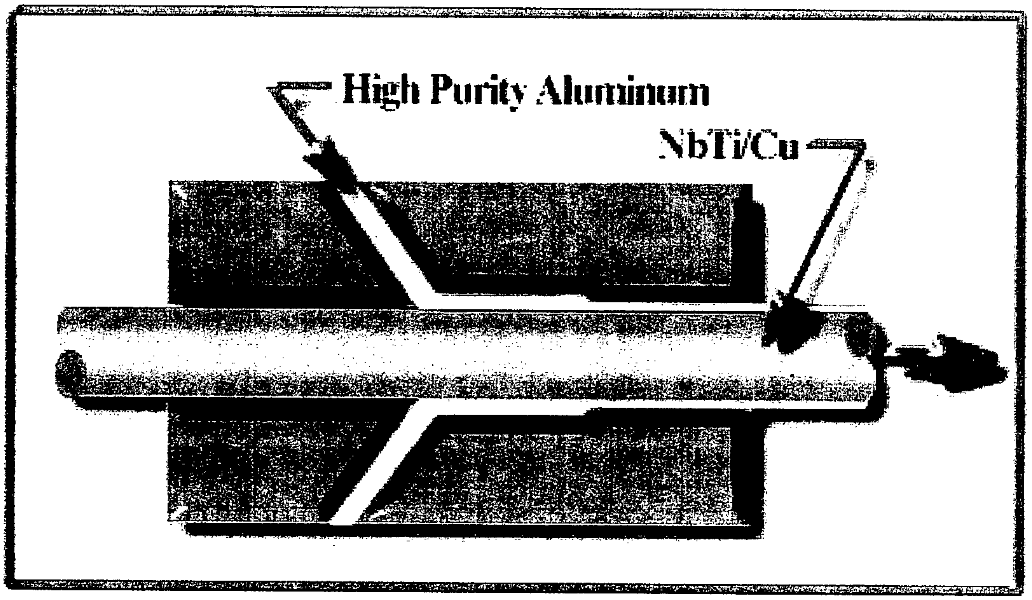

Figure 3-1. Schematic of aluminum hot co-extrusion.

This process requires development to decrease the production time and eliminate the need to recharge the aluminum to the system several times during the operation. In order to add the aluminum to the system, the process must be stopped. This results in the core wire overheating and ultimately the deterioration of superconducting properties. The current process is slow compared with other processing methods and it is also costly and risky. A typical production run for 30,000 feet of wire takes several days of continuous operation to complete. In addition, high tooling and equipment costs have limited the use of hot co-extrusion.

3.3 LINEAR WRAPPING AND WELDING

The linear wrapping and welding method is an adaptation of the unique tubular wire manufacturing process which has been used by the welding industry for over 30

years to produce powder core welding wires. By applying this manufacturing technology to aluminum cladding, very long superconducting wires can be manufactured as shown in Figure 3-2.

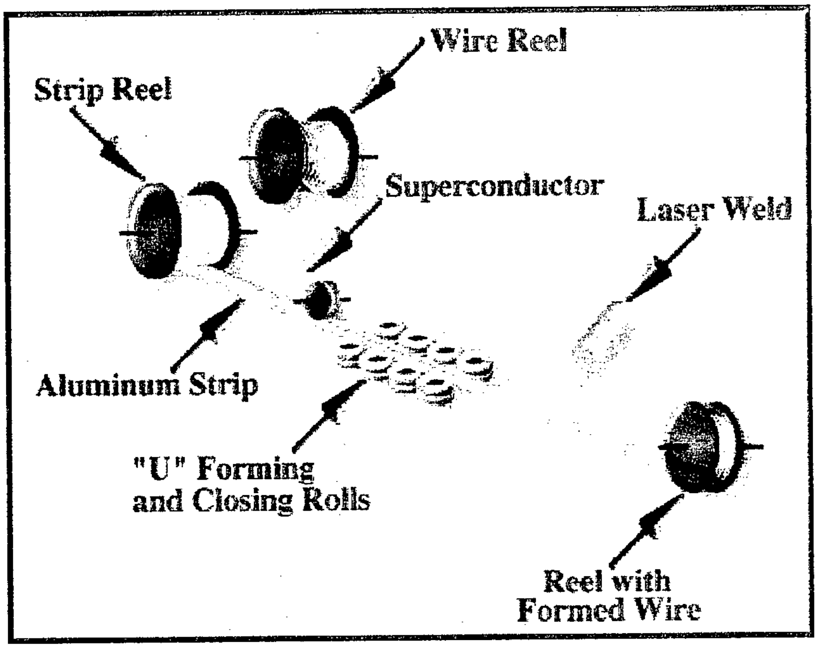

Figure 3-2. Schematic of linear wrapping and welding.

In this process, the superconducting core wire and the aluminum strip are fed continuously into a set of forming and closing rolls. Here, the aluminum strip is formed into a U-shape, compressed tightly around the core wire, and subsequently welded using a laser beam. The aluminum strip thickness affects the core wire sizes which are larger than necessary (0.020 inches) and therefore require additional wire drawing operations. Due to significant differences in the yield strength of pure aluminum and that of the core conductor (NbTi/Cu matrix), it is not technically feasible to draw aluminum clad superconductors without additional reinforcement of pure aluminum. This may be accomplished by linear wrapping of copper foil over the aluminum foil. After the wire drawing operation and prior to final shaping, the copper can be chemically removed. As mentioned earlier, the strength of the bond between the aluminum and the copper matrix is critical to the thermal stability of the conductor. In order to create a mechanical or

metallurgical bond, prior to linear wrapping, a low-temperature coating has to be applied to both the core wire and to the aluminum strip. To remelt the coating, induction heating could be either incorporated in the linear wrapping stage or performed independently before the wire drawing process.

The linear wrapping method offers the advantage of continuous processing and is limited only by the length of the core wire. In addition, the process can be discontinued without affecting the superconducting properties of the conductor. The simplicity of this process will result in low capital cost and consequently lower conductor cost relative to the hot co-extrusion process.

3.4 RADIAL (SPIRAL) WRAPPING

The spiral wrapping method is used commercially in the production of a paper-insulated magnet wire where a thin tape, generally 0.0025 inches thick, is spirally wrapped in single or multiple layers around the conductor. With this method, multiple layers are created by having individual tapes positioned to overlap the preceding tape by a specified percentage of the tape's width. This method can use high-purity aluminum spirally wrapped onto a superconducting NbTi/Cu wire. Although there are several methods available, it appears that the best method of spiral wrapping is the "one-half overlap" method depicted in Figure 3-3.

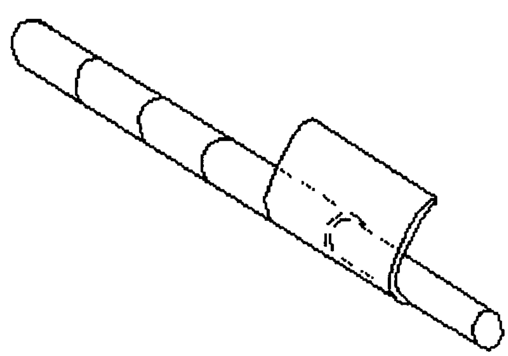

Figure 3-3. Schematic of the one-half overlap spiral wrapping method.

As mentioned previously, however, the bonding between aluminum and the core wire (copper) is critical to the conductor's thermal stability. The spiral wrapping itself cannot create strong mechanical or metallurgical bonds. Therefore, soldering and ultrasonic welding methods need to be considered. In the soldering method, a thin layer of solder can be applied to both the aluminum foil and the wire before spiral wrapping. After it is wrapped, the assembly is heated by induction to melt the solder. The molten solder will bond the foil and the wire and the foil overlap layers. There are several methods of applying the solder to aluminum foil, with electroplating preferred over other soldering methods because it does not require heating the foil.

Copper and aluminum can be joined together using ultrasonic welding, with two clear benefits over the soldering method. First, the pre-tinning step can be avoided, saving both money and time. Second, solder interfaces can be eliminated, improving thermal and electrical conductivity. In order to ultrasonically weld the aluminum to itself and to copper, prototype tooling must be developed, built, and tested. This tooling is shown in Figure 3-4.

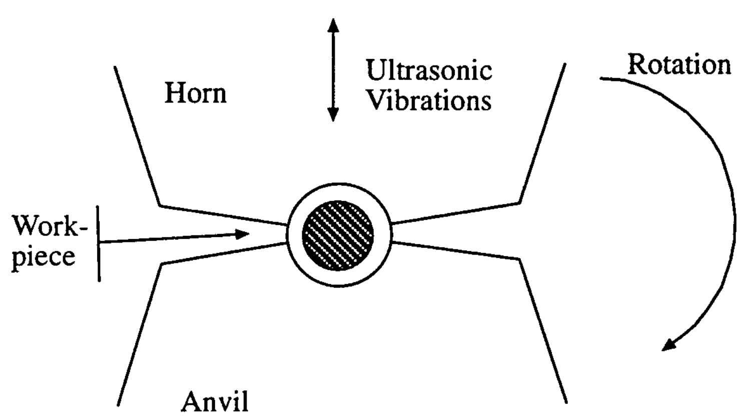

Figure 3-4. Schematic of ultrasonic welding fixture.

The spiral wrapping method offers the advantage of continuous processing. In addition, the process can be stopped without affecting the superconducting properties of the conductor. Critical to the practical application of this method, however, is the quality of the bond between aluminum and copper. Due to its technological simplicity and the

low capital cost, the spiral wrapping method offers lowest process cost from all investigated methods.

3.5 MOLTEN METAL COATING

Composite Concepts Company (CCC) has developed a proprietary hot dip process, as depicted in Figure 3-5, for producing steel core wires with zinc-enriched brass coatings used in the electrodischarge machining (EDM) industry. In this process, the core wire is adequately cleaned so that it can be wetted by the liquid metal, which is in a crucible with a hole in the bottom. The core wire is guided continuously through the liquid metal. A metallurgically bonded coating solidifies on the cooler substrate. The diameter of the composite wire is continuously monitored by a laser micrometer (an integral part of the proprietary control system that maintains the diameter). This process can be adjusted for different core wire sizes as well as for variations in the coating thickness.

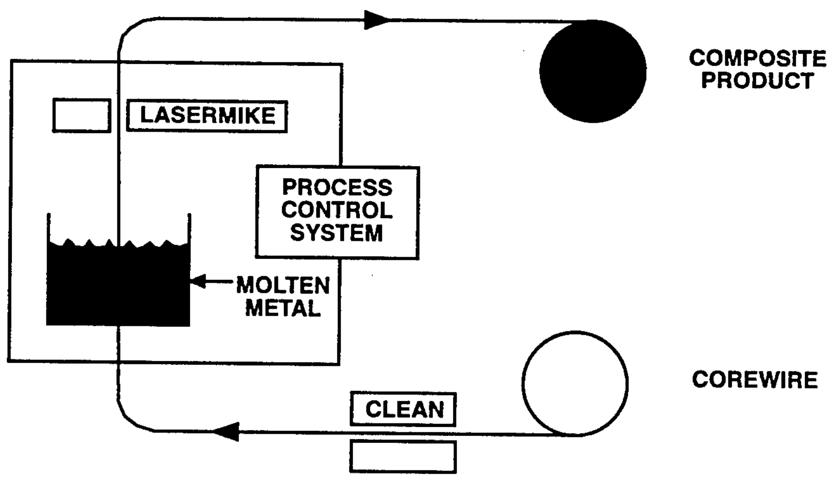

Figure 3-5. Schematic diagram of the Composite Concepts Company (CCC) hot dip process.

The CCC process can also be applied to other metallurgical systems, including a system for coating commercially pure aluminum on a plain carbon substrate. This coating maintains its integrity even after a 92% reduction in area.

The NCEMT's goal is to use molten metal technology to clad pure aluminum onto the superconducting wire. Because the coating thickness can be controlled, it is possible to optimize the aluminum to superconducting core ratio. Aluminum can also be clad directly to a rectangular cross section, thus eliminating the need for shaping the wire mechanically. Also, due to the low forming stress of molten clad material, the likelihood of filament breakage and "sausaging" is substantially reduced. A clear advantage of this process is its ability to improve production speed and thereby lower production costs. However, the risk of conductor overheating and the loss of superconducting properties is present.

3.6 ELECTROPLATING

Aluminum can be eletrolytically deposited on a superconducting wire using anhydrous electrolytes composed of fused mixtures of aluminum chloride and alkali chlorides. Pure chemicals and high-purity aluminum anodes are required because all metallic impurities that are below aluminum in the electromotive series interfere with the production of a smooth, bright, adherent coating. This type of coating is free from any interfacial alloy layer. Containers for the fused salt bath are constructed with aluminum to avoid contamination of the bath. Before aluminum deposition begins, dissolved moisture and metallic impurities are removed from the bath by electrolysis or by treatment with scrap aluminum. Because fuming is severe, good ventilation is required. Aluminum can also be electroplated from several anhydrous organic electrolytes. Another plating bath consists of aluminum chloride and lithium hydride in an ethyl ether solvent. This bath must be prepared, used, and stored within a gas-tight enclosure containing a dry inert atmosphere. Parts to be plated proceed through an air lock chamber, which is purged with dry nitrogen gas. After parts are plated, they are removed in a similar fashion. A deposition rate of 25 μm (0.001 inches) to 50 μm (0.002 inches)

per hour is used. A thickness of 500 µm (0.020 inches) can be reached, which is sufficient for obtaining the desired 2:1 aluminum to core ratio.

Even though the aluminum electroplating process is a viable alternative to other cladding methods, the purity of the aluminum coating could be a concern. Thermal stability of the superconducting core requires an aluminum purity of 99.999%. The best produced coatings had a purity of 99.99+%.

4.0 DISCUSSION

While the technical assessment section deals primarily with benefits and limitations of each aluminum cladding method, other factors such as conductor cost and the Advanced Lightweight Influence Sweep System (ALISS) Advanced Technology Demonstration (ATD) schedule have to be considered before a specific conductor manufacturing process is selected.

Of the five different approaches available for aluminum cladding, extrusion and electroplating methods are least applicable due to their batch-type operations with inherently limited conductor plating length capability. While the proof-of-concept demonstration for both these processes could be successful, full-scale production runs of 30,000 feet in length are not possible in the given time frame for the functional ALISS demonstration. Given these schedule constraints, the NCEMT will focus its efforts on processes that can assure cost effective and technically feasible production. For these reasons, extrusion and electroplating processes will not be experimentally evaluated.

The three other methods of aluminum cladding include radial wrapping, linear wrapping, and molten metal coating. While each method may have some technical challenges, all three methods have capabilities to continuously clad aluminum for required conductor lengths. In addition, the equipment for wrapping other tape materials onto copper, steel, or aluminum wires, is available commercially and can be adapted to this process.

Based on the evaluative efforts at the NCEMT and the NSWC, the most technically feasible and affordable method will be selected for further development. This

technique will be optimized either at the NCEMT or at the facility of a commercial company interested in the manufacture of aluminum-stabilized NbTi superconductors.

5.0 SUMMARY

A thorough review of the technical literature and presentations at the workshop on aluminum stabilization of the NbTi superconductors indicate that aluminum cladding efforts date back to the late 1970's. The approaches that were investigated used both external and internal stabilization of aluminum. Efforts were also concentrated on all aluminum matrix conductors design. In all cases, only small experimental lengths of the conductor were manufactured for the NSWC evaluation. The co-extrusion method was preferred for its capability to produce metallurgical bonds between the copper matrix and the high purity aluminum. However, the process is limited in its capability to clad very long conductors and is very costly.

The cladding technology covered the whole range of materials and methods. The NCEMT's technical feasibility study concentrated on five specific cladding technologies that could be applied to the aluminum cladding of NbTi superconductors. These were radial wrapping, linear wrapping, molten metal dip coating, extrusion, and electroplating. The extrusion and electroplating methods are the least applicable due to their batch-type operations, with inherently limited conductor plating length capability and high equipment cost. The other methods are radial wrapping, linear wrapping and molten metal dip coating. While each method may have some technical challenges, all three have capabilities to continuously clad aluminum for the required conductor lengths. However, while this assessment provides reasonable conclusions on the technical feasibility of a specific cladding process, the cost analysis can be applied only to the results of the experimental work. Based on the evaluative efforts at the NCEMT and the NSWC, the most technically feasible and affordable method will be selected for further development.

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